PALEOFLOODS AND FLOOD FREQUENCY IN THE ARKANSAS RIVER BASIN NEAR PUEBLO, COLORADO

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Abstract: We investigate extreme flood hydrology for dam safety risk analysis in the 12,000 km^2 Arkansas River watershed above Pueblo, Colorado. Historical and paleoflood data are collected in order to significantly extend peak-flow records from streamflow-gaging stations for flood frequency analysis. Paleofloods and paleohydrologic nonexceedance bounds are estimated at four locations within the basin: near Salida, Cotopaxi, Parkdale, and near Pueblo. These sites are strategically selected to describe the transition from snowmelt-dominated to rainfall-dominated floods. At each of the four sites, soils were described and charcoal samples were collected for radiocarbon dating. The four reaches were surveyed and modeled with HEC-RAS in order to determine the discharge required to overtop specific geomorphic surfaces. Paleohydrologic bound ages at the four sites ranged from 400 to 2,200 years B.P. for younger surfaces. A Pleistocene bound (10,000 to 14,000 years) was estimated near Cotopaxi. Peak discharges ranged from about 17,000 ft^3/s near Salida to 130,000 to 160,000 ft^3/s near Pueblo. Historical information at Pueblo since 1859 were used in conjunction with paleoflood data to place the record June 1921 flood in proper time context between about 150 and 700 years. Peak-flow frequency was conducted using available gage, historical and paleoflood data at each location with the Expected Moments Algorithm. The frequency curves show the transition between snowmelt peaks upstream of the Royal Gorge and very large rainfall-dominated peaks downstream near Pueblo.

INTRODUCTION

Paleoflood data is a critical component for assessing hydrologic hazards at Reclamation dams. By providing information beyond the historical gaging record, it typically serves as the only data for directing the flood frequency curve beyond the 100-year return period. It also provides an important check for the validity of flood frequency and rainfall-runoff modeling results because it is based on direct observations of the physical system. Through field-based studies, hydraulic modeling, and laboratory analysis, a paleoflood hydrology study can provide data on the magnitude and frequency of floods and/or can provide a limit to flood magnitude over a specified time interval. When used in flood frequency analysis, paleoflood data can greatly improve the flood hazard estimation for return periods beyond the period of record, compared to other extrapolation methods. When extreme floods or "high outliers" are present in the record, such as the record June 1921 flood on the Arkansas River (Follansbee and Sawyer, 1948), their return period may be much greater than the period of record. Placing a large historical flood into context with geological deposits provides a more accurate estimate of the true return period of the extreme flood.

Paleoflood investigations and peak discharge probability estimates were made at four main sites within the 12,000 km^2 Arkansas River basin: the Arkansas River at Pueblo State Park near Pueblo; the Arkansas River at Parkdale; the Arkansas River at Wellsville (Loma Linda); and the Arkansas River at Salida (Figure 1). Paleoflood peak discharge estimates, and estimates of paleohydrologic bounds, were combined with available historical information and peak discharge estimates from gaging stations at these sites.

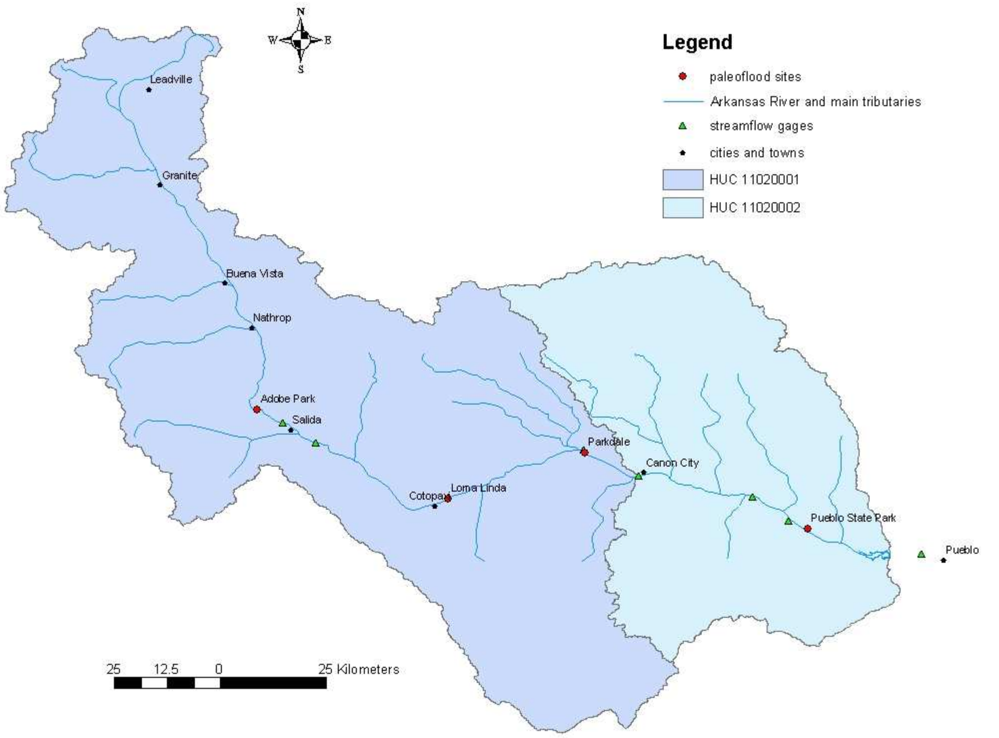

Figure 1. Locations of four paleoflood study sites within the Arkansas River basin.

PALEOFLOOD INVESTIGATIONS

Field investigations were conducted at the four sites shown in Figure 1. Soil and stratigraphic data were gathered at each site along stream bank exposures or in hand dug pits approximately 2 ft wide and 3 ft deep. Soil properties and sedimentary structures were described using terminology from Birkeland (1999). To estimate the age of terraces, individual charcoal pieces and bulk sediment were collected. These samples were floated for macrobotanical materials, which were then identified to a species level by Paleo Research Institute. Selected samples underwent radiocarbon analysis, which determines the age of a sample based on the principles of the radioactive decay of the carbon atom, at Beta Analytic, Inc. These ages can then be used in conjunction with soil data and used to interpret the age of the stratigraphy of the stream terrace and any individual flood deposits preserved in the stratigraphic record.

Each detailed study area was mapped based on aerial photo interpretation, using field observations, and existing geologic data. Geomorphic mapping is very useful for placing study sites into their proper geologic context. The geomorphic maps compiled for this study show the distribution of Pleistocene and Holocene alluvium, the location of bedrock, HEC-RAS hydraulic model cross sections, and soil pit locations where stratigraphic and age data were collected. The study reach for Pueblo State Park is shown in Figure 2. Three soils pits were dug at this site. Soils profiles for two pits are shown in Figure 3. Paleoflood data collected at the four sites is summarized in Table 1. Complete details of the data and analyses are in England et al. (2005).

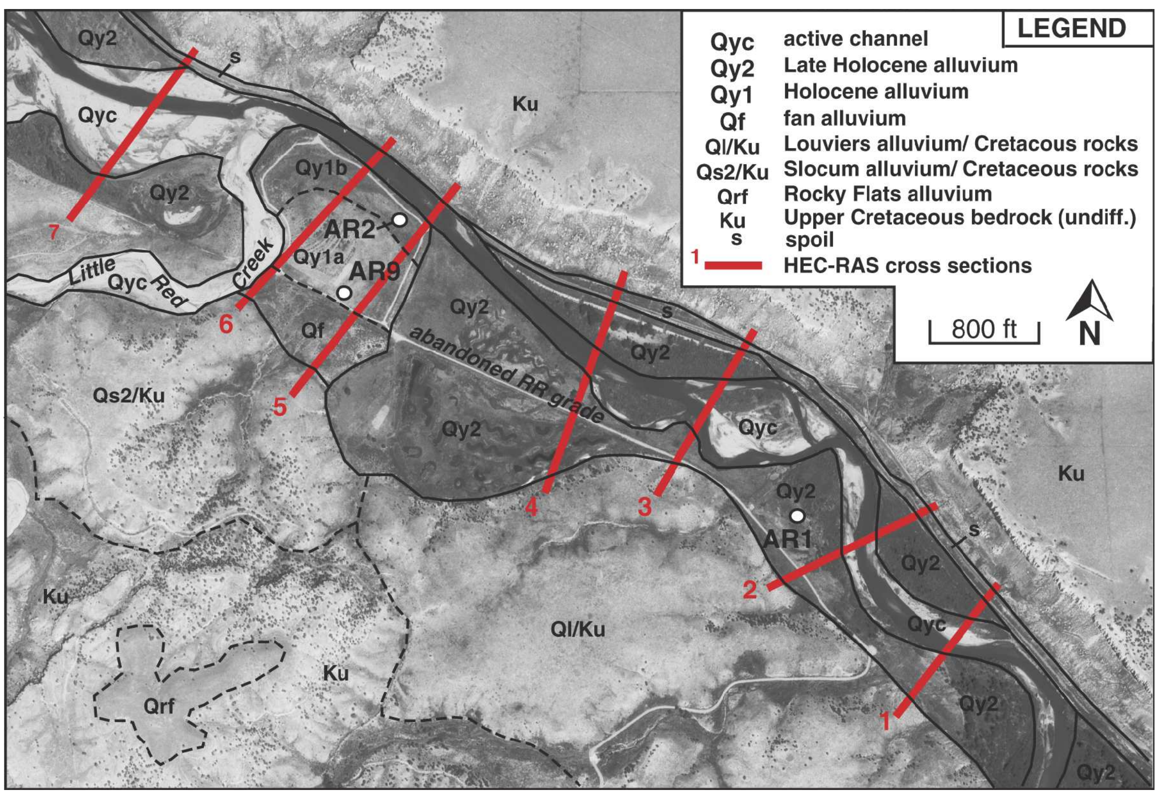

Figure 2. Geomorphic map of the Arkansas River in Pueblo State Park reach upstream of the dam and reservoir. River flow is from upper left to lower right.

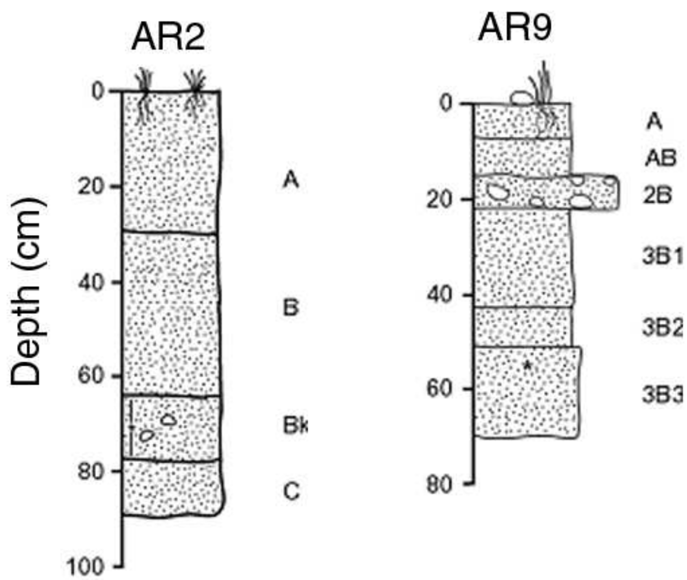

Figure 3. Schematic profiles of soils at sites AR2 and AR9 (Pueblo State Park). Sample AR2-3JU collected from the interval 63-78 cm yielded a radiocarbon age of 1750±40 (1740-1550 cal yrs B.P.). Sample AR9-1JU collected from 56 cm yielded a radiocarbon age of 830±40 (790-680 cal yrs B.P.).

Table 1: Summary of Paleoflood Nonexceedance Bounds, Upper Arkansas River

Location	Stratigraphic Site	Type of Estimate	Age Range (years)	Peak Discharge Range (ft^3/s)
Pueblo State Park	AR9	nonexceedance bound	730-840	130,000-160,000
Parkdale	AR5	paleoflood	historical (post 1870)	18,000-22,000
	AR3, AR4	nonexceedance bound	1100-1300	24,000-34,000
Loma Linda	AR7	nonexceedance bound	700-2200	13,000-18,000
	AR6	nonexceedance bound	10,000-14,000	50,000-60,000
Adobe Park	AR8	nonexceedance bound	400-600	17,000-27,000

FLOOD FREQUENCY

Peak-flow frequency estimates were made for annual instantaneous peak discharge estimates. Peak discharge probabilities are estimated directly from the data using Cunnane's plotting position with the threshold-exceedance formula (Stedinger et al., 1993) that includes historical and paleoflood data. The data were assumed to follow a log-Pearson Type III (LP-III) distribution. The method of moments was used to estimate the LP-III parameters for peak discharge estimates using Expected Moments Algorithm (EMA) techniques (Cohn et al., 1997). EMA (Cohn et al., 1997, 2001; England et al., 2003) is a new moments-based parameter estimation procedure that was designed to incorporate many different types of systematic, historical, and paleoflood data into flood frequency analysis. A simplified regional frequency analysis was conducted for the four sites with paleoflood data, using the index flood method

(Stedinger et al., 1993). The regional frequency analysis was conducted to compare the distributions from each site for "consistency" in a qualitative sense. The goal was to determine if the estimated frequency curve for the Arkansas River immediately upstream of Pueblo was similar to frequency curves from the other three sites. Similarity in the frequency curve at Pueblo, to those from other sites, would provide additional confidence in estimating extreme flood probabilities at Pueblo Dam. Differences between the frequency curves could clearly highlight mixed-population flood effects within the basin.

Based on reviews of available historical information, including Follansbee and Jones (1922), Munn and Savage (1922), and Follansbee and Sawyer (1948) (among others), there is a substantial amount of historical flood information on the Arkansas River in Pueblo that was usable for frequency analysis. The historical record was estimated to begin in 1859, resulting in a 146-year period (1859-2004). The criteria for inclusion of historical floods in frequency analysis were: the ability to rank the floods relative to the June 1921 event; and to estimate magnitudes for the individual floods. A time series plot of the peak discharge, historical flood and paleohydrologic bound data is shown in Figure 4. Three historical floods were included: June 1864, July 1893, and May 1894; all have relatively large uncertainties as compared to the smaller floods in the gage record (Figure 4).

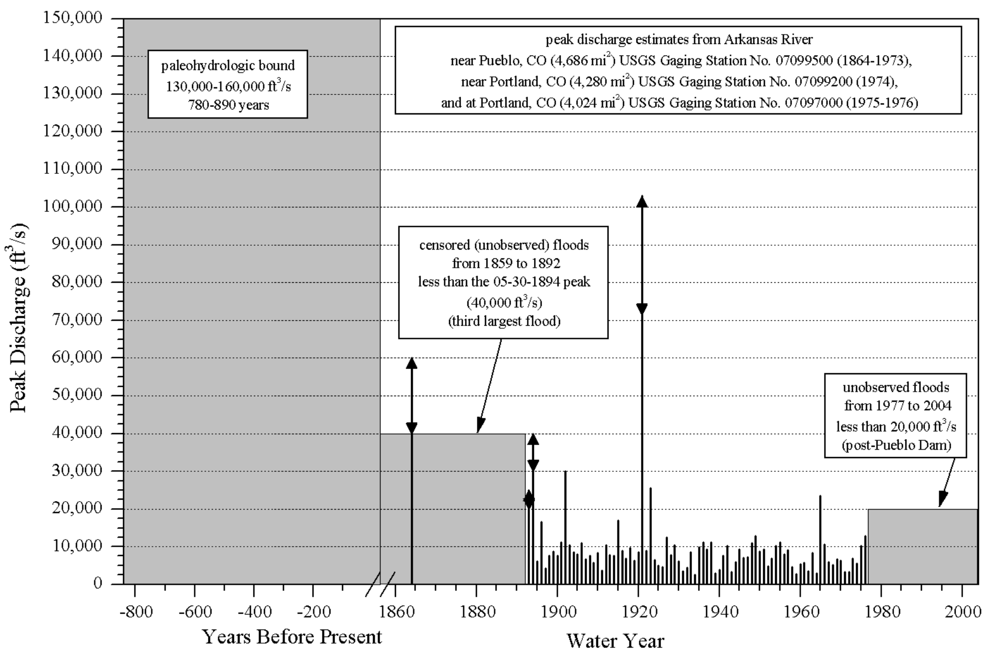

Figure 4. Approximate unregulated peak discharge, historical and paleoflood estimates, Arkansas River at Pueblo Dam. A scale break is used to separate the gage and historical data from the longer paleoflood record. Arrows on the 1864, 1893, 1894 and 1921 floods indicate floods in a range.

The flood frequency results for this site are shown in Figure 5. Peak discharge estimates from the gage are shown as open squares with estimated data uncertainty for some of the largest floods that were described in a range. One can observe the large positive skew (0.8 log space) and relatively steep transition between snowmelt-dominant floods to rainfall dominant floods greater than about 10,000 ft^3/s. These large rainfall-caused floods are responsible for the shape of the upper portion of the frequency curve. The return period of the largest flood on record (June 1921) is about 270 years from the exceedance-based plotting position, and about 1,600 years from the LP-III model. The model fits the bulk of the data well, including most of the large floods, but undershoots the largest flood (June 1921) due to the addition of paleoflood data. The paleohydrologic bound data at Pueblo State Park increases the peak discharge record length substantially to about 840 years, and has an effect on the upper end of the extrapolated frequency curve principally by reducing the skewness coefficient. One can estimate design flood probabilities based on significant extrapolation of the LP-III model and 90 percent confidence interval (Figure 5). The spillway design outflow capacity for Pueblo Dam (191,000 ft^3/s) has an estimated return period of 13,000 years, and a return period estimate for the volume-critical spillway design inflow peak (270,000 ft^3/s) is about 42,000 years.

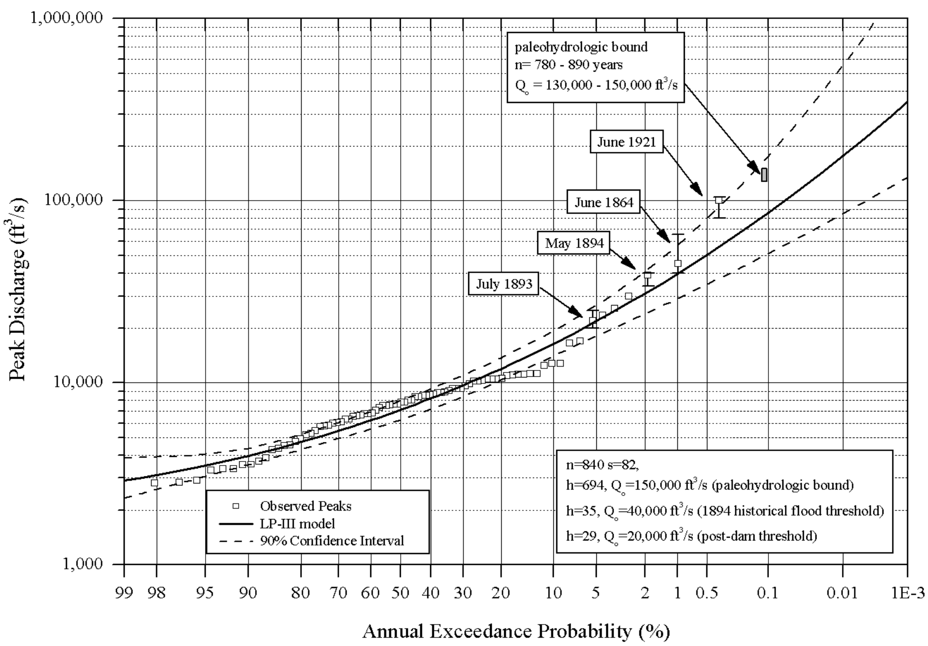

Figure 5. Approximate peak discharge frequency curve, Arkansas River at Pueblo State Park, including gage, historical and paleoflood data.

Non-dimensional peak discharge frequency curves, based on LP-III models derived from the data set at each site, are shown in Figure 6. The at-site 10-year peak discharge was used to non-dimensionalize the flood frequency model results. The lower-basin frequency curves (Pueblo and Parkdale) clearly reflect rainstorms (mixed-population snowmelt and large rainstorms), whereas the upper basin sites (Loma Linda and Adobe Park) are from snowmelt. The frequency curves for the downstream locations are clearly different for the most extreme floods; they have a much steeper shape. The curvature is primarily determined by the LP-III model skewness coefficient. The log-space skew is positive at Pueblo (0.8) and Parkdale (0.3), and negative at Loma Linda (-0.2) and Adobe Park (-0.2). The extreme peak-flow magnitudes at Pueblo are substantially larger than at upstream locations within the same time period, giving a much steeper frequency curve. The shapes and slopes of the Adobe Park and Loma Linda frequency curves are very similar, and are clearly different than the two downstream locations. The streamflow and paleoflood data do not show any evidence of extreme floods substantially larger than that recorded in the gage record for the upper basin snowmelt locations. The Parkdale frequency curve is similar in shape to the upstream curves for flows less than about the 10-year peak. This suggests a separation in flood process in the record; the upper end of the Parkdale frequency curve behaves similarly to Pueblo, but is not as steep. One can infer from this that there is a transition in peak-flow frequency behavior between Pueblo and Loma Linda; storms that affect Pueblo and cause extreme floods do not cause as large peaks at Parkdale. The results show that the use of a partial-area storm concept on the lower part of the basin is warranted.

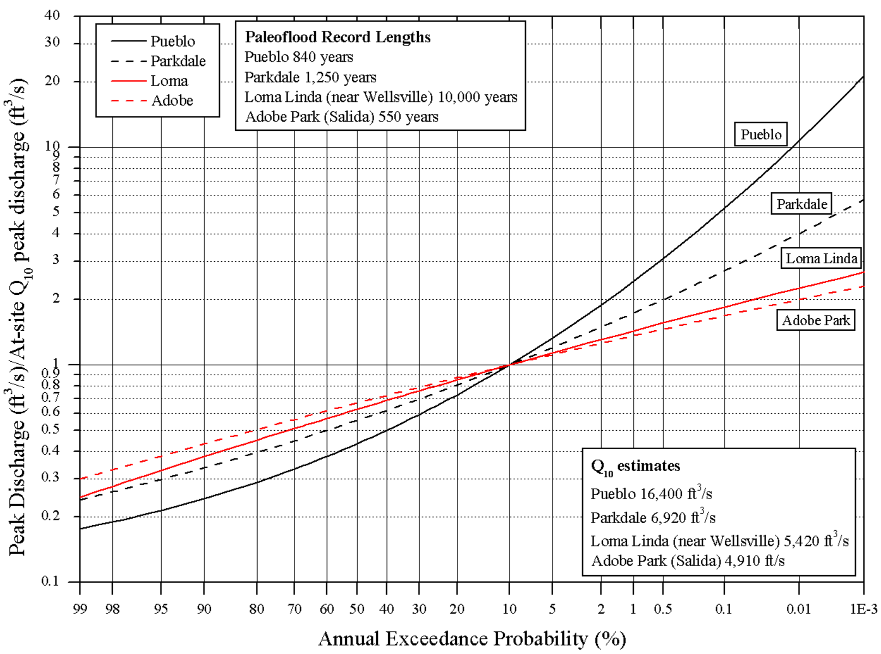

Figure 6. Approximate unregulated non-dimensional peak discharge frequency curves for the four sites within the Arkansas River basin. Each curve is non-dimensionalized by its respective at-site 10-year model peak flow.

SUMMARY

Flood frequency analysis was conducted using peak-flow (gage), historical and paleoflood data at four locations along the main stem of the Arkansas River upstream from Pueblo, as part of dam safety assessments for Pueblo Dam. Details of this work, including paleoflood data, hydraulic modeling, frequency analysis, and rainfall-runoff modeling at these locations are presented in England et al. (2005). The Expected Moments Algorithm was used with the LP-III distribution to estimate flood frequency curves at Pueblo, Parkdale, Loma Linda (Wellsville) and Adobe Park (Salida). Confidence intervals for each frequency curve were also estimated. Paleohydrologic bounds spanned 550 to 10,000 years within the watershed and provided substantially longer record lengths for frequency analysis. Peak flows in the lower watershed at Pueblo and Parkdale reflected extreme floods from rainfall, and were relatively much larger than at the two upstream locations. The lower sites had positive log-space skews. The largest floods at upstream sites were from snowmelt; these locations had relatively flat frequency curves and negative log-space skews. Using a regional index-flood approach, it was shown that there is a different population of floods between upstream snowmelt and downstream rainfall-runoff sites. The frequency curves are subsequently used to contrast flood frequency curves estimated with a rainfall-runoff model.

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